Dynamics of cross-industry low-carbon innovation in energy-intensive industries

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Abstract

Technological innovations in energy-intensive industries (EIIs) have traditionally emerged within the boundaries of a specific sector. Now that these industries are facing the challenges of deep decarbonisation and a significant reduction in greenhouse gas (GHG) emissions is expected to be achieved across sectors, cross-industry collaboration is becoming increasingly relevant for low-carbon innovation. Accessing knowledge and other resources from other industrial sectors as well as co-developing innovative concepts around industrial symbiosis can be mutually beneficial in the search for fossil-free feedstocks and emissions reductions. In order to harness the potential of this type of innovation, it is important to understand not only the technical innovations themselves, but in particular the non-technical influencing factors that can drive the successful implementation of cross-industry collaborative innovation projects.

The scientific state of the art does not provide much insight into this particular area of research. Therefore, this paper builds on three separate strands of innovation theory (cross-industry innovation, low-carbon innovation and innovation in EIIs) and takes an explorative case-study approach to identify key influencing factors for cross-industry collaboration for low-carbon innovation in EIIs.

For this purpose, a broad empirical database built within the European joint research project *REINVENT* is analysed. The results from this project provide deep insights into the dynamics of low-carbon innovation projects of selected EIIs. Furthermore, the paper draws on insights from the research project *SCI4Climate.NRW*. This project serves as the scientific competence centre for *IN4Climate.NRW*, a unique initiative formed by politicians, industry and science to promote, among other activities, cross-industry collaboration for the implementation of a climate-neutral industry in the German federal state of North Rhine-Westphalia (NRW).

Based on the results of the case study analysis, five key influencing factors are identified that drive the implementation of cross-industry collaboration for low-carbon innovation in EIIs: Cross-industry innovation projects benefit from *institutionalised cross-industry exchange* and *professional project management and coordination*. Identifying opportunities for *regional integration* as well as the *mitigation of financial risk* can also foster collaboration. Lastly, *clear political framework conditions* across industrial sectors are a key driver.

Introduction

The need for deep decarbonisation is one of the key challenges facing EIIs in the twenty-first century. It requires radical technological innovation, as key production processes need to be replaced by fossil-free, emissions-free alternatives. Incremental efficiency improvements are no longer sufficient and traditional innovation strategies within sectoral and organisational boundaries are beginning to reach their limits. Companies have started looking beyond their own industries in the search for knowledge, technologies and resources that can help them decarbonise their production processes. This assumption can be derived at least from the results of two projects dealing with low-carbon innovations in energy-intensive industries, *REINVENT*[1] and *SCI4Climate.NRW*[2].

This paper therefore addresses the role that cross-industry collaboration can play for low-carbon innovation in EIIs, and at the non-technical factors that influence these cross-industry innovations. With this rather explorative approach we aim to generate inductively derived findings on the following research question: What are key factors influencing the successful implementation of cross-industry collaboration projects for low-carbon innovation in EIIs?

The qualitative data collected in the projects *REINVENT* and *SCI4Climate.NRW* provide first insights into possible influencing factors of such innovation processes. The data are derived from a total of four case studies, three of which were carried out within the *REINVENT* project and the fourth case comprises the *SCI4Climate.NRW* project, as an independent case outside the *REINVENT* project. In addition to these case studies, a brief overview of the relevant literature in the fields of cross-industry innovation, low-carbon innovation and innovation in EIIs is given here in order to be able to make a possible classification of the observations resulting from the cases into theoretical approaches. Using this exploratory approach, we describe patterns in the four cases and interpret them based on the literature review. In doing so, we arrive at a set of five key factors that can drive cross-industry innovation to decarbonise EII.

Cross-industry innovation – a fairly recent concept

Innovation strategies of companies in the 20th century could mostly be attributed to the so-called *closed innovation* approach. Internal research and development (R&D) departments would rarely leave defined company boundaries. Ideas were either developed directly inside the R&D department or generated elsewhere in the company and subsequently internally developed, produced and marketed. This way, a company could boost its competitiveness by investing more in R&D than its competitors did, and use the resulting time advantage and generated profit to stay ahead in the next iteration of the innovation cycle. While this inwardly focused approach worked well with the knowledge landscape at the time, later developments forced the companies to rethink their innovation strategy: R&D cycles grew shorter, development costs rose rapidly and securing internal knowledge became more difficult as the number and mobility of knowledge workers increased. As venture capital became more readily available, it got easier for innovators to leave established companies and instead develop their ideas in start-ups. Knowledge, as the key to identifying and exploiting innovations, is therefore more readily available, leading companies to open up their innovation process (Chesbrough, 2003; Mölter et al., 2017).

This *open innovation* approach describes a new paradigm, which combines both internally and externally generated knowledge and ideas. Open innovation alliances can take the shape of *horizontal collaboration*, in which competitors with different capabilities co-operate, or *vertical collaboration* with suppliers and customers. Depending on the direction of the knowledge flow, the open innovation may be referred to as an *inside-out process* (sale or licencing of a technology to others) or *outside-in process* (stakeholder integration and external sourcing of technology). An open innovation process that combines both is referred to as a *coupled process*, which may take the shape of a strategic alliance or joint venture (Inauen & Schenker-Wicki, 2011; World Economic Forum, 2012).

Incumbent organisations spend the vast majority of their technology budgets on upgrading existing technologies (Roberts, 2007), especially if innovation cycles are long and costly as in many EIIs. This type of incremental innovation reaches its limits when companies are forced to seek more radical innovation. This happens under a certain pressure on their industries, for example when the political signs point to decarbonisation and switch to fossil-free feedstocks. Existing solutions in one industry are oftentimes not sufficient for generating radical innovation, leading companies to search for solutions (i.e. knowledge, technologies or products) also outside traditional industry boundaries (Hahn, 2015). This can happen in the form of *outside-in cross-industry innovation*, in which organisations adapt established solutions from other industries (Gassmann et al., 2011). It can also take the shape of horizontal collaboration between two or more companies across industry lines. The formation of such *cross-industry innovation alliances* is still a fairly new topic both in academic literature and industrial practice (Hahn, 2015). Companies rarely perform cross-industry assessment as part of their innovation strategies (Nolf et al., 2012), which is why the role of intermediaries in such collaborative ventures has received some attention (see e.g. Gassmann et al., 2011). Such open innovation processes also often follow more of a trial-and-error approach instead of a professionally managed process. This has drawn some criticism, as a more systematic approach to cross-industry innovation promises better economic outputs (Hahn, 2015).

Low-carbon innovation – in search of a holistic approach

The debate around climate change mitigation as a societal and economic imperative has bred countless concepts surrounding sustainable development and innovation. Earlier work focussed more on *eco-innovations*, i.e. products, processes and organisational forms that help reduce different kinds of negative environmental impacts (e.g. Rennings, 2000), while later work took a more holistic view on sustainability, covering both environmental and social aspects in a range of terms such as *sustainable, sustainability-driven* or *sustainability-oriented innovation* (e.g. Arthur D. Little (ADL), 2005; Klewitz & Hansen, 2014; Wüstenhagen, 2008).

Adams et al. (2012) observe a somewhat parallel development from a *reactive* approach to sustainable innovation in the early 1990s (i.e. companies making incremental low-carbon innovations in response to specific changes in regulations or market conditions) to a more *proactive* approach (i.e. companies innovating out of a broader perspective on their activities' social and environmental impact). The authors also differentiate between two schools of thought in research on sustainability-oriented innovation: one focussing on a series of step-wise innovation in a desired direction *(incremental innovation)* and one emphasising the need for larger, more disruptive transfor-

1. https://www.reinvent-project.eu/
2. https://www.in4climate.nrw/en/stakeholders/scientific-community/

mation *(radical innovation)*. Lema et al. (2015), among others, take the latter approach, citing Schumpeter's *'creative destruction'* (Schumpeter, 1942) to emphasise the need for the dismantlement of existing economic systems in order to create more sustainable ones in their place.

Low-carbon innovation falls within the scope of sustainable innovation but tends to be defined more narrowly, focussing on a reduction of GHG emissions while not necessarily covering other planetary issues such as water scarcity or biodiversity loss (Lema et al., 2015). Polzin (2017, p. 525) describes it as "the development and diffusion of clean technologies (eco-innovation) with simultaneous withdrawal from carbon-intensive technologies based on fossil fuels". This emphasises two aspects of low-carbon innovations: a reduction or avoidance of GHG emissions (through "clean" technologies) and the phasing-out of fossil fuels. Other publications see the latter aspect as less of a necessary precondition than the former: Technologies for *carbon capture and utilisation (CCU)* and *carbon capture and storage (CCS)* are often mentioned in the context of low-carbon innovation, as they are designed to prevent carbon emissions from escaping into the atmosphere, while still allowing for the use of fossil fuels (e.g. Liu & Liang, 2011).

A strong focus on technological solutions is often applied in the context of low-carbon innovation, while a more holistic view also includes non-technical types of innovations (e.g. social innovation, business model innovation) that are aimed at reducing GHG emissions (e.g. Bergmann et al., 2010). Bell (2009) argues that for low-carbon innovation the *direction* of innovation is more important than the *rate* of innovation. Bergmann et al. (2010) call attention to the fact that defining low-carbon innovation as "innovation that contributes to reduction in carbon emissions from human activities" could refer either to the *intention* behind the innovation or to its *outcome*, and that the two may not coincide. The authors go on to argue that both motivation and impact of the innovation should be of relevance when describing an innovation as low-carbon.

Innovation in energy-intensive industries – a lack of customers

Energy-intensive industries like steel, chemicals, paper or cement are a crucial part of the global economy, producing the basic materials that we use for infrastructure, buildings, transportation, machinery and a vast range of consumer goods. As their production processes require very high levels of energy and resource inputs, they are also responsible for a large amount of GHG emissions. In recent decades, these industries have made considerable improvements in energy and resource efficiency by means of incremental process innovations. However, this approach is no longer sufficient in the light of the target set by the Paris Agreement to keep global warming well below 2 °C. The goal of reaching net-zero emissions requires more extensive and more radical low-carbon innovation, which includes the development of entirely new core production processes. Such processes are needed to either replace fossil feedstock with renewable resources, fossil fuels with renewable energy (electricity, hydrogen) or apply CCS or CCU where this is an option. Thus, compared to other industrial branches, EIIs are met with unique challenges both from a technical and an innovation perspective (Åhman et al., 2017; Wesseling et al., 2017).

Continuous incremental efficiency improvements aside, most production processes in EIIs have remained practically the same for decades. The market for basic materials is a highly competitive commodity market largely driven by price. Industry structure is characterized by high capital intensity, large variations in prices, low profit margins, and long payback times, investment cycles and equipment lifetimes. The market is ruled by large incumbents, which creates high barriers to market entry and leads to inertia. With the exception of the chemicals industry, R&D investment in EIIs is low compared to other industries, consequently resulting in low rates of innovation. Scaling up radical innovation is costly and oftentimes risky, and the economies of scale achieved in established technologies are difficult to compete with (Wesseling et al., 2017).

Radical process innovations in EIIs have occurred sporadically in the past and were mainly motivated by economic incentives (e.g. through increased product quality, production capacity or energy savings), which is not currently the case for the required low-carbon innovations (Åhman et al., 2017). So far, there is a lack of both supply and demand for low-carbon basic materials, which may be due to the fact that industries and their products are far from the end-consumer. Because there is no market advantage to be expected from marketing a material's low-carbon properties, companies have had little incentive to invest in costly new production processes, as currently there appears to be no willingness on the part of customers and the general public (end users) to accept price increases (Wesseling et al., 2017).

Research Methodology

CONCEPTUAL CLASSIFICATION OF THE RESEARCH QUESTION

The three previous sections have made it clear that three main strands of innovation theories can currently be used for the conceptual classification of the research question: What are key factors influencing the successful implementation of cross-industry collaboration projects for low-carbon innovation in EIIs? These three strands include the relatively recent phenomenon of *cross-sectoral innovation,* a less holistic approach to *low-carbon innovation* and the specific characteristics of *innovation in energy-intensive industries*. Thus, if we want to take a closer look at cross-industry collaboration for low-carbon innovations here, the conceptual focus is on the specific intersection of these theoretical strands, as Figure 1 illustrates. Whether this conceptual focus can be further developed beyond this paper to answer the present research questions will have to be examined in future research

RESEARCH APPROACH

Due to the explorative nature of this research question and the lack of pre-existing work on this specific interface of innovation approaches, we follow an inductive research approach, "in which the researcher uses observations to build an abstraction or to describe a picture of the phenomenon that is being studied" (Lodico et al., 2010).

RESEARCH DESIGN

The explorative research design of the already mentioned *REINVENT* project comprises a multi-step qualitative analysis of data collected, by means of expert interviews and desktop

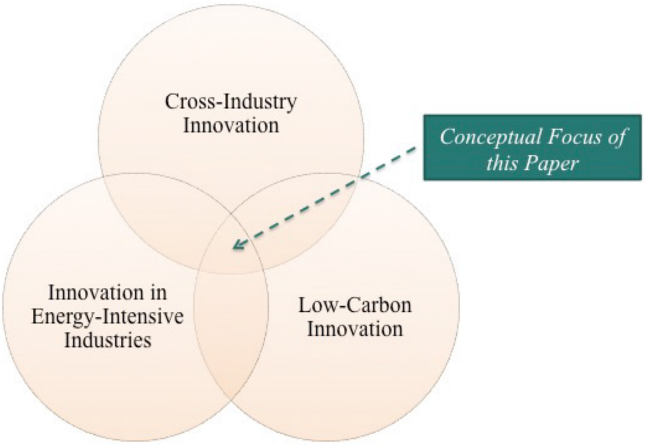

Figure 1. Cross-industry low-carbon innovation in EIIs as the intersection of a Venn diagram.

research, for 18 different innovation case studies (conducted between 2018 and 2019). The case study work focussed on low-carbon innovations in four different EIIs (steel, plastic, paper, meat & dairy). The cross-industry collaboration aspect, with which we are particularly concerned in this paper, was originally not explicitly operationalised as a separate research question. However, in addition to a number of other research themes within the project, a special focus was placed on the non-technical drivers and barriers in the implementation of the various innovation projects, and from this research dimension the importance of cross-industry collaboration became increasingly clear in the semi-structured interviews and the evaluation.

1. The specific research question addressed in this paper arose during and especially after the completion of the case study work[3]. In order to check whether this research question can be dealt with on the basis of the existing database, all 18 *REINVENT* cases were therefore examined in a first analytical step for aspects of cross-industry collaboration[4]. Three cases were found that can be categorized as cross-industry low-carbon innovation projects in EIIs based on the literature review and were thus chosen for further analysis. In addition to the data from the REINVENT project, we decided to add the IN4Climate.NRW initiative as a fourth case study to the analysis conducted in this paper. While no in-depth case study was undertaken for this in the REINVENT project, the initiative is of unique interest for the analytical scope of this paper: It is a multi-industry organisational innovation whose purpose lies in fostering further radical low-carbon innovation in EIIs. In addition, one of the other innovation cases studied in this paper (Carbon2Chem) laid some of the groundwork for the IN4Climate.NRW initiative. Lastly, the research project SCI4Climate.NRW, which accompanies the initiative from a scientific perspective, is led by the Wuppertal Institute, allowing for easy access to expert information.
2. In a second analytical step, a qualitative content analysis of the data collected for the three *REINVENT* cases (interview data, desktop research) as well as *IN4Climate.NRW* (desktop research, internal communication within the *SCI4Climate.NRW* project) is conducted, focussing on the different influencing factors driving the implementation of each specific cross-industry innovation project. For *IN4Climate.NRW*, special attention is also paid to the ways in which *IN4Climate.NRW* (as a platform for collaboration) and *SCI4Climate.NRW* (as a hub for the creation and exchange of knowledge) themselves aim to drive the implementation of cross-industry low-carbon innovation projects. The four cases and the specific drivers found in the content analysis are described in the following chapter.
3. In a final aggregative step, by means of categorising and comparing the observed drivers and barriers, five key influencing factors that drive cross-industry collaboration for low-carbon innovation in EIIs are identified. These influencing factors are also discussed along the three theoretical strands in the corresponding chapter.

POTENTIAL LIMITATIONS

There are some inherent limitations to this paper and its methodology. Only a small selection of cases is analysed, which does not cover the whole range of EIIs. One reason for this is that although the case selection in the *REINVENT* project was limited to low-carbon innovations in EIIs, the criterion of cross-industry collaboration did not originally play a role. Hence, the number of cross-industry cases was purely coincidental. Not least, however, it is also due to the fact that EIIs are still in the early stages of their low-carbon transformation and that there are not yet many cross-industry innovations in this area. Therefore, the paper cannot claim to present drivers and barriers of cross-industry innovation in EIIs in their full range, but only to show the non-technical factors that need to be considered in order to drive them forward.

In-Depth Case Studies

ENERKEM WASTE-TO-CHEMICALS PLANT, ROTTERDAM, THE NETHERLANDS

Canadian technology provider *Enerkem* has developed a chemical recycling technology that produces syngas from (hydro) carbon wastes, such as biomass and plastics. The syngas is converted to methanol, which can be used to produce a range of (intermediate) chemicals. As part of a big cross-industry consortium, *Enerkem* is now planning to build their first European plant within the industrial cluster at the *Port of Rotterdam* (Bauer et al., n.d.; Tönjes et al., 2019). The initiative for the Rotterdam plant started as a collaboration of *Enerkem* (a Canadian technology provider), *AkzoNobel* (now *Nouryon*, a chemical producer), *Air Liquide* (a supplier of industrial gases), *Renewi* (a waste management company) and the *Port of Rotterdam* (Europe's largest seaport and major industrial logistics hub). A few players changed over time, with *Renewi* leaving the project and

3. Summary report of case studies available here: https://static1.squarespace.com/static/59f0cb986957da5faf64971e/t/5d23b2550832210001a02b65/1562620507471/D3.3+Summary+of+Decarbonisation+Case+Studies.pdf.

4. Report on non-technical drivers and barriers available here: https://static1.squarespace.com/static/59f0cb986957da5faf64971e/t/5dc41e4149d3b81baca39f62/1573133911248/D3.6+Drivers+of+low-carbon+innovation.pdf.

Shell (bio-fuels) becoming a partner. The project receives public funding from the Government of The Netherlands, the Province of Zuid-Holland and the City of Rotterdam (Bauer et al., n.d.). The technology was originally developed with the aim of tackling waste disposal and low-carbon transportation (Bauer et al., n.d.). At its Canadian plants, the company converts the methanol to ethanol (Chornet et al., 2009), which is recognised as bio-ethanol for automotive fuel application under the U.S. Renewable Fuel Standard (Stolte, 2018). This conversion step is not necessary if there is a market for bio-methanol. While the timing for the planned Rotterdam site seemed to also be driven by European regulatory developments on biofuel standards, the methanol produced at the facility is expected to be used mainly as feedstock for chemicals production at adjacent sites of *Nouryon* and *Shell.* The question of the chemicals' application is key, and so is the collaboration with the chemical producer (Bauer et al., n.d.).

The *Port of Rotterdam* has an interest in keeping investments and employment in the area, and has set out to become the 'most sustainable port in the world'. It is actively searching for new technologies and markets that can help sustainably transform and decarbonise the largely fossil-based cluster. This is a valuable perspective in terms of pushing cross-industry innovation: Recognising the cluster's unique opportunities of bringing together the existing waste management system and local chemical production was key – and ultimately influenced *Enerkem's* decision to pick Rotterdam as the site for its first European plant. Even with the *Port of Rotterdam* bringing the different parties to the table, a big hurdle to overcome was and is the complexity of the project and large number of involved parties. Each partner brings their own perspective, shaped by their individual background. This led to big challenges in the initial phase of forming a project consortium and continues to be a considerable barrier as it makes processes more complex and slow-moving (Bauer et al., n.d.).

A key barrier to project implementation lay in the large amount of capital required for the waste-to-chemicals (W2C) plant, which turned out to be relatively difficult to obtain. The final investment decision is, at the time of writing, still pending. But the project has many positive aspects (e.g. important players involved and innovative sustainable promise) that could help to obtain the funding (Bauer et al., n.d.).

While the basic technology to convert municipal waste into methanol is already in commercial use at *Enerkem's* Canadian site, the complexity of the cross-industrial project does not allow for a simple "copy and paste" approach. Transferring the technology from Edmonton to Rotterdam is only one part of the equation, *Enerkem's* expertise is only part of the knowledge needed for the innovative project to succeed. The technology provider's project partners' expertise covers many other areas along the W2C value chain: Adapting to the local waste management system, considering requirements for different potential uses of the resulting methanol, a range of questions of logistics and infrastructure, taking into account national and EU policy on waste treatment and biofuels, etc. Since *Renewi* left the consortium, there is no company from the waste sector committed to the project, so the project is now lacking this kind of expertise. The search for downstream co-operators from the chemical industry also continues (Bauer et al., n.d.).

The W2C project is seen as a first step toward more industrial symbiosis (i.e. "the process by which wastes or by-products of an industry or industrial process become the raw materials for another" (European Commission, 2018)) and a more circular economy: On the one end of the value chain, *Nouryon* acts as a supplier of hydrogen, a by-product of its chlorine production. On the other end of the value chain, the bio-methanol can then be supplied back to the chemical industry as a feedstock for the production of a range of chemicals, some of which will end up back in the waste stream. If the project turned out a commercial success, it could function as a blueprint for the development of a knowledge cluster on waste-to-value technologies (van Arkel, 2018).

DURASENSE BIOCOMPOSITE, HYLTEBRUK, SWEDEN

In 2014, Finnish pulp and paper company *Stora Enso* launched an R&D project to develop a biocomposite material. In collaboration with small local enterprises with expertise in plastic converting, it developed *DuraSense*; in 2018, first products made from the new material were launched (Tönjes et al., 2019). *DuraSense* is quite literally a product of cross-sectoral innovation: By embedding wood fibres in plastic, the material has properties that cannot be achieved by either component individually. Biocomposites are already used in a wide range of applications, from automotive upholstery to indoor furniture to noise insulating panels (La Mantia & Morreale, 2011).

The innovation process was born out of a need to diversify. In the Swedish town of Hyltebruk, two paper machines operated by *Stora Enso* had to be shut down in 2014, raising the question of other potential business opportunities that could benefit from existing knowledge and infrastructure, as well as newly freed-up resources, space and equipment. Engineers with experience in the pulp and paper industry were hired to strengthen the project's research competence. In order to fill in large gaps in expertise on the plastics side, different forms of informal collaboration with other (downstream) companies (e.g. *Orthex,* a manufacturer of plastic household goods) were initiated. This allowed them to understand the market, identify product needs and ensure functionality along the value chain. One way in which collaboration was realised was through the organisation of workshops with machinery development firms, polymer suppliers and other actors along the value chain. While there was no formal collaboration between equal partners (e.g. a joint venture), cross-industry cooperation was nevertheless crucial. By working with firms developing equipment for compounding plastics, injection moulding experts and plastic converters, *Stora Enso* ensured an iterative development process for testing the material took place as development progressed. Instead of working with a partner from the plastics industry equal to them in size, *Stora Enso* chose to collaborate with smaller, regional firms to test the material's properties. It was deemed easier to collaborate with smaller yet well-established companies in order to minimise bureaucratic friction, sacrificing scale for easy coordination. Rather than forming a large joint venture, the collaboration was built on trust and proximity (Bauer et al., n.d.).

While the *DuraSense* innovation process is more incremental in nature than the other cases covered in this paper, it can still be considered an important step toward more cross-industry innovation for a biobased economy. Moving towards the production of chemicals in biorefineries has been quite difficult. Biocomposites can be seen as a way for the pulp and paper industry to move toward producing chemicals and plastics, although still firmly connected to the production of fibres, which is at the core of the industry's knowledge (Bauer et al., n.d.).

CARBON2CHEM CHEMICALS FROM BLAST FURNACE OFF-GASES, NRW, GERMANY

The *Carbon2Chem* project, established in 2016, is a large-scale collaborative innovation project at the intersection of the steel and chemicals industries. The CCU technology allows blast furnace off-gases from the steel industry to serve as a raw material for the production of chemicals for applications such as fuels, fertilizers and plastics. The project is mainly located in NRW, a federal state of Germany that is home to many companies operating in EIIs. The project was initiated by steelmaker *Thyssenkrupp* and two research institutions, *Fraunhofer Institute for Environmental, Safety and Energy Technology (UMSICHT)* and *Max-Planck-Institute for Chemical Energy Conversion (MPI CEC)*. The consortium grew to include 18 partners from industry and science, including large chemicals producers like *BASF, Covestro* and *Evonik*. The overall investment for the first project period (2016-2020) is 84 million EUR; until commercialisation, project partners expect to invest over 1 billion EUR (BMBF, 2016). The project aims for industrial application within 15 years (Bauer et al., n.d.; Tönjes et al., 2019).

One general advantage of collaboration between big corporations from different industries is that there is no issue of direct competition. The large *Carbon2Chem* consortium, however, contains direct competitors from the chemical industry. Issues of compliance and confidentiality slowed down the process until the contracts were signed. In the same vein, another important hurdle to overcome is what could be described as a "language barrier" between companies from different industries, as well as between industries and research partners: Partners had different understandings of certain processes. A main barrier was bringing this diverse group of corporations and research institutions together in a safe environment and with tools and structures in place to implement a steady dialogue and exchange of knowledge . As with the other cases, geographical proximity and regional characteristics were essential driving factors for Carbon2Chem. The steel and chemical industries in NRW are located closely together (Bauer et al., n.d.). This is especially key for innovation projects involving industrial symbiosis: The supplier of the resource (in this case the steel industry) and the consumer of the resource need to be physically close together to minimize the need for transport and building of additional infrastructure.

Members of the *Carbon2Chem* consortium have stated that climate policy has been a key driver for the project. The German government's Climate Protection Plan 2050 as well as the European Union's Emissions Trading Scheme (EU ETS) were stated to have motivated project initiation, while the Paris Agreement was perceived as a "wake-up call" regarding the growing need for taking concrete steps toward deep decarbonisation. The case of *Carbon2Chem* shows that the role of government actors in cross-industry collaboration projects should not be underestimated. A competition between "top clusters," initiated by the German Federal Ministry of Education and Research (BMBF) and aiming for the exploitation of cross-industry potentials regarding the saving of resources, can be seen as a starting point. It brought the steel and chemicals industries together and – even though the proposal for the competition was not accepted – the newly established contacts remained intact and exchange continued. The BMBF's competition led to the evolvement of *CleanTech.NRW*, a regional platform aimed at bringing businesses together, which helped lay the groundwork for the creation of *Carbon2Chem*. The BMBF also played an important role by providing EUR 62 million in public funding, which helped mitigate some of the risk posed to the consortium by the prospect of a long research phase and the lack of a working business case. This also helped to establish the BMBF as a facilitator and provider of structure in the project by putting certain funding requirements in place (e.g. involving board members from all companies in a steering committee which monitors the project). The BMBF can be seen as an enabler for more visibility, higher legitimisation and increased transparency, while the support and expertise from external research facilities on an overarching level is also considered to be a key success factor (Bauer et al., n.d.).

Carbon2Chem shows how cross-industry innovation projects can build on one another. *Carbon2Chem* was, in itself, a pioneering project in terms of sheer size, complexity, and investment volume. It was also the foundation for the creation of the *IN4Climate.NRW* initiative, which is much larger and more complex still. The organisational set-up and methodology of *Carbon2Chem* facilitated a more targeted and informed organisational process for the initiative, as is outlined in the following chapter.

IN4CLIMATE.NRW, AN INITIATIVE FROM INDUSTRY, SCIENCE AND GOVERNMENT, GERMANY

As described in the case of *Carbon2Chem*, the German federal state of NRW is a hub for EIIs including, but not limited to, chemicals, steel, non-ferrous metals, glass and paper. These industries are an important mainstay of the state's economy, providing jobs to over 1,370,000 people, around 19.6 % of NRW's total workforce. It is also responsible for 54.7 million tonnes CO_2 emissions in 2017, which is 19.9 % of NRW's total emissions. *IN4climate.NRW* was created by the Ministry of Economic Affairs, Innovation, Digitalisation and Energy of the State of NRW (MWIDE) as a platform for dialogue and collaboration between experts from industry, science and politics. Their shared goal is to develop innovative strategies and solutions for climate-neutral industrial products and processes. Specifically, the initiative aims to develop a coherent picture of a climate-neutral and resource-efficient basic materials industry, create technology roadmaps, foster bigger pilot projects and the testing of business cases, build up a knowledge hub for the transition to a climate-neutral basic materials industry in NRW, and show expedient framework conditions on a state, federal and EU policy level (IN4climate.NRW, n.d.).

The initiative consists of a complex organisational structure to ensure its functionality across the many represented fields of expertise and broad range of objectives. This includes the Head Office coordinating the initiative, industry partners participating in a continuous dialogue process, and the research project *SCI4Climate.NRW*, which supports the work of the initiative from a scientific perspective. Industry partners include big industry associations as well as important players including steelmaker *thyssenkrupp*, chemicals producer *covestro*, *Heidelberg Cement* and many others. The Head Office coordinates all organisational activities, connects the initiative to national and international networks and identifies opportunities for funding and publication. Industry actors, researchers from the *SCI-4Climate.NRW* consortium and representatives of the MWIDE convene regularly in plenary meetings ("innovation teams"). The innovation teams have formed working groups that get together in a regular workshop format and focus on cross-cutting issues that affect EII players in NRW, such as the role of hydrogen, the establishment of the necessary framework conditions or the building of a circular economy. Exchange between different working groups is also crucial at certain points of intersection (IN4climate.NRW, n.d.).

The research project

The SCI4climate.NRW research project is the initiative's scientific competence centre, carried by six leading research institutes: *Wuppertal Institute, Fraunhofer UMSICHT, German Economic Institute (IW), RWTH Aachen University, VDEh Institute for Applied Research (BFI)* and the *German Cement Manufacturer's Association (VDZ)*. The project is designed to show possible ways to achieve a climate-neutral, energy-intensive industry in NRW, in close cooperation with the *IN4climate.NRW* initiative and the industrial companies working within it. This results in a complex field of research that must react flexibly to current political processes and initiatives of the industry so that the results can also have an impact, for example, on the design of possible infrastructures in NRW. *SCI4Climate's* different Topic Fields cover a range of perspectives: technology, process chain, overall system integration, and framework conditions. Connections are drawn and dialogue fostered between the topic fields and the innovation teams' working groups to ensure a holistic approach and avoid information asymmetry (SCI4climate.NRW, n.d.).

The coordination between the research project and the broader initiative has an important place within the research project's organisational structure, ensuring a smooth exchange between the scientific base and the industrial and governmental actors. There are workshops and other formats for exchange to facilitate the understanding and documentation of the external and internal links within and between the project's diverse subject areas and establish a collaboration reflecting this understanding. This includes exchange about strategic issues like the identification of relevant research questions or possibilities for the creation of innovative business models in EIIs (SCI4climate.NRW, n.d.).

SCI4Climate.NRW also includes a "Scientific Academy", a project-internal exchange and training programme intended to create a culture of discussion in the project and thus enable a deeper mutual understanding of the background knowledge of the research partners' specific topics. While this includes the discussion of project-related topics, it is also explicitly designed to cover thematically more extensive subjects, both reflecting and strengthening the project's innovative capacity. The industrial collaboration across sectors that distinguishes the initiative is thus reflected in the interdisciplinary cross-topic collaboration within the research project (SCI4climate.NRW, n.d.).

First results

In the scope of this paper, the *IN4Climate.NRW* initiative is a special case: It is, in itself, a big cross-industry organisational innovation project, unique in its size and complexity, while at the same time aiming to foster other cross-industry innovation projects. The initiative has begun to generate first results. A discussion paper on the potential role of hydrogen for industry in NRW[5] was published in October 2019 as a contribution to the development of the national hydrogen strategy by the Hydrogen Working Group. The Circular Economy Working Group has produced a concept paper on the perspectives of chemical recycling for plastic waste as a common ground for the group's future work. Overall, a lot of mutual learning has already taken place in the different working groups. Industry and scientific partners have benefitted from collaboration: Industry actors gain an overview of the current scientific state of the art as well as future perspective through the researchers' modelling and scenario work. Research institutions gain insight into issues that drive industry actors in real time as well as different options, technological or otherwise, that companies are considering. All partners have benefitted from learning each other's languages and perspectives. The initiative's work so far has shown that through the creation of an institutionalised regional network, possibilities for dialogue and exchange can open up on a national or European level as well. In terms of political engagement, *IN4Climate.NRW* is providing a platform for companies to develop and communicate joined political positions and demand, instead of large companies and industry associations always representing their own interests separately. While the initiative is still in early stages, *IN4Climate.NRW* has helped create the necessary conditions for cross-industry collaboration, joint proposals and innovative R&D projects to take place (IN4climate.NRW, n.d.).

Analysis and Discussion

From the analysis of the case study reports, as well as through understanding the different ways in which the *IN4Climate.NRW* initiative aims to foster cross-industry innovation in NRW, five key factors can be identified that can drive the implementation of cross-industry low-carbon innovation projects in EIIs.

(1) MITIGATION OF FINANCIAL RISK

As established in the literature review, R&D spending is comparatively low in the capital-intensive EIIs, with the exception of the chemicals industry. Radical innovation in the past has been motivated mainly by economic incentives. There was a return on investment to be expected through increased productivity, the use of better feedstocks or large efficiency gains. This sort of business case is often lacking for businesses looking to invest in radical low-carbon innovations. Scaling up new innovative production technologies is expensive, and there is no significant customer base willing to pay a premium for the materials' low-carbon properties. This is why many low-carbon innovation projects peter out in early stages of R&D.

5. Discussion paper available here: https://www.in4climate.nrw/newsroom/publikationen/.

Cross-industry innovation can provide some solutions for these issues: By starting collaboration at the beginning of the innovation process, companies can share some of the financial risk. Bringing a commercial consumer in early (like *Enerkem* collaborating with chemicals producers in the W2C project) can mitigate financial insecurity and help create a business case. *IN4Climate.NRW* also fosters the development of innovative low-carbon business models that can help in the creation of business cases through cross-industry collaboration. Furthermore, large cross-industry consortia tackling GHG emissions can also attract public funding, which can further improve financial prospects and can help involved partners to make an investment decision. Public funding played a role in all cross-industry innovation projects analysed for this paper except for *DuraSense* (which could be attributed to special circumstances after the shutting-down of the paper mills that freed up a lot of resources).

(2) POLITICAL FRAMEWORK CONDITIONS

The literature on low-carbon innovation shows that there has been a shift among companies from a reactive to a more proactive approach to low-carbon innovation. The case study results indicate that this shift has continued, as companies are opening up to looking across company and industry lines to move toward deep decarbonisation, thus taking the opportunity to shape the upcoming change themselves. The *Port of Rotterdam*, for example, has set itself the goal of becoming the world's most sustainable port. In the *Carbon2Chem* case study, the importance of the companies joining such complicated projects of their own accord became clear. Many industrial actors in NRW were motivated to join the *IN4Climate.NRW* initiative early on. The case studies revealed that big political signals like the Paris Agreement as well as clear framework conditions like the EU ETS play a key role for this shift in mind-set.

(3) INSTITUTIONALISED CROSS-INDUSTRY EXCHANGE

The search for knowledge, technologies and resources outside traditional industry lines can be an important driver for radical innovation. However, the literature review also revealed that companies rarely assess opportunities across industry lines as part of their innovation strategies. Cross-industry innovation is therefore often driven by opportunities for cross-industry exchange provided by third parties, such as government actors. This came through particularly clearly in the case of *Carbon2Chem*, which came together as the result of the Top Clusters competition and the *CleanTech.NRW* platform, and which in turn influenced the creation of *IN4Climate.NRW.* The platform, again initiated by government actors, has institutionalised this cross-industry exchange, and much of their work lies in the creation of opportunities for exchange between different EIIs. It provides a platform, neutral spaces and formats for targeted discussion and the exchange of knowledge and ideas. In this context, the role of scientific actors for the exchange, collection and processing of knowledge in big cross-industry consortia should also be mentioned.

(4) PROFESSIONAL MANAGEMENT AND COORDINATION

Once cross-industry exchange has taken place and an idea for an innovation project has formed, the diversity and large number of actors continues to be a key barrier to success. Large, complex innovation consortia comprising a wide range of different partners with different perspectives, knowledge bases and interests are slow-moving and involve a lot of bureaucratic "red tape". This can slow down and impede development, the signing of contracts and final investment decisions, leaving the project vulnerable to the withdrawal of key partners. The literature showed that a point of criticism regarding open innovation processes is that they often follow trial-and-error approaches instead of professionally managed processes. For cross-industry innovation, this can be particularly problematic: Organising on-going work, preventing information asymmetries and maintaining mutual trust is a big task that often cannot be carried by one of the partners. The *DuraSense* case revealed that avoiding bureaucratic hurdles was one of the reasons *Stora Enso* decided to collaborate with smaller companies in an informal manner. For many cross-industry innovation projects, this is not an option, so that this organisational barrier needs to be overcome in a different way.

The case of *Carbon2Chem* shows the importance of having a professional structure in place, in this case enforced through funding requirements set by the BMBF. *IN4Climate.NRW* built on this insight, constructing a detailed organisational structure that does justice to the complexity of the initiative and its members and designating several different levels of project management. In these cases, government actors took on key coordinating roles but this can also be fulfilled by non-governmental actors. The *Port of Rotterdam*, for example, has a unique position in the W2C project as it has an interest in bringing innovation to the region and representing the interests of the companies already located in the industrial cluster surrounding the port.

(5) REGIONAL INTEGRATION

Regional proximity of partners can be a key driver for cross-industry innovation projects – even beyond practical considerations around infrastructure. In the case of *DuraSense, Stora Enso* as the main actor chose partners for collaboration based on proximity rather than size. In the W2C project, Rotterdam was chosen as a site for the first European *Enerkem* plant because of the strong presence of the chemical industry in the cluster. In *Carbon2Chem,* NRW as a hub for both steel and chemical industry, as well as a strong research landscape, provided the necessary conditions for such a large industrial symbiosis endeavour. This was a first step toward institutionalising regional integration, which was then taken to a higher level in the *IN4Climate.NRW* initiative, showing how regional integration can be a multiplier for cross-industry innovation. In regions and clusters where such collaboration takes place, partners and facilitators can use the knowledge and experience they gain to initiate new collaborative innovation projects and shape them in a beneficial manner.

Conclusions

Cross-industry collaboration for low-carbon innovation in EIIs is still a fairly new phenomenon; most of the innovation projects analysed for this paper are still in early stages, so that no conclusions can be drawn on the successful implementation of the innovations themselves, nor their contribution to the decarbonisation of these industries. However, some key factors have been identified that can influence the initiation and successful implementation of such cross-industry collaboration projects: the opportunity to mitigate financial risk and attract funding, clear political framework conditions, the institutionalisation of cross-industry exchange, professional project management and coordination, as well as opportunities for regional integration can all drive collaborative innovation processes. Actively fostering collaboration through shaping these factors can thus contribute to the decarbonisation of EIIs, as cross-industry exchange and collaboration can help companies from different industries identify common goals and needs, which may lead to the formation of new pathways that may otherwise have been left unexplored.

Some of the factors identified in this paper that influence the successful implementation of cross-sectoral innovation are also reflected in the three theoretical strands of innovation theories. For example, radical low-carbon innovations are costly and risky for industry, as the theoretical approach to *Innovation in Energy-Intensive Industries* shows. The cases have made it clear that this inertia can be partially broken through clear political framework conditions and financial support. The various forms of cross-industry cooperation in the cases studied are reflected in the theoretical strand on *Cross-Industry Innovation*, from horizontal to outside-in cooperation, to the finding that all these efforts are often still characterized by trial-and-error approaches. Finally, the cases also reveal that there is no pre-existing theoretical transformation approach that can be used as a blueprint for the practical implementation of decarbonisation of EIIs. The cases presented in this paper should provide a contribution and further impulses for sharpening the existing theoretical approaches or for building a new, holistic theoretical approach. Many aspects of cross-industry collaboration are still unclear, for example the role of trusting relationships for stable collaboration. Future research could also build on these results by analysing the role of the identified key factors in other cross-industry low-carbon innovation cases and identifying other potential influencing factors. As these innovations progress, one could also expand on the research by identifying driving factors in later stages of R&D, roll-out and scale-up. Lastly, the potential contribution of cross-industry innovation for deep decarbonisation in EIIs could be further explored. Its benefits could be weighed against potential trade-offs, such as potential carbon lock-in effects resulting from industrial symbiosis.

Bibliography

Adams, R., Jeanrenaud, S., Bessant, J., Overy, P., & Denyer, D. (2012). *Innovating for Sustainability. A Systematic Review of the Body of Knowledge*. Network for Business Sustainability.

Åhman, M., Nilsson, L. J., & Johansson, B. (2017). Global climate policy and deep decarbonization of energy-intensive industries. *Climate Policy*, *17* (5), 634–649. https://doi.org/10.1080/14693062.2016.1167009

van Arkel, L. (2018). *Statenvoorstel – Randvoorwaarden Waste to Chemistry* (Provincie Zuid-Holland, Ed.; PZH-2018-634468381). https://www.zuid-holland.nl/publish/pages/19257/a1_statenvoorstel_-_randvoorwaarden_waste_to_chemistry.pdf

Arthur D. Little (ADL). (2005). *Innovation High Ground Report: How Leading Companies Are Using Sustainability-driven Innovation to Win Tomorrow's Customers*.

Bauer, F., Bengtsson Sonesson, L., Cooper, M., Ericsson, K., Hasselbach, J., Knoop, K., Kobiela, G., Kushnir, D., Lane, R., Mölter, H., Negro, S., Nikoleris, A., Nilsson, L. J., Pastowski, A., Tönjes, A., Tziva, M., van Veelen, B., Witte, K., & Worrell, E. (n.d.). *REINVENT decarbonisation case studies.* To be published: https://www.reinvent-project.eu/documentation.

Bell, M. (2009). *Innovation Capabilities and Directions of Development*. STEPS Centre. https://opendocs.ids.ac.uk/opendocs/handle/20.500.12413/2457

Bergmann, N., Markusson, N., Connor, P., Middlemiss, L., & Ricci, M. (2010, February). *Bottom-up, social innovation for addressing climate change*. Sussex Energy Group conference – eceee 2010, Brighton, UK.

BMBF. (2016, June 27). *Auf einen Blick: „Carbon2Chem"*. https://d13qmi8c46i38w.cloudfront.net/media/UCPthyssenkruppAG/assets.files/media/c2c/presse/27_06_16_kurzdarstellung.pdf

Chesbrough, H. W. (2003). *Open innovation: The new imperative for creating and profiting from technology* (Nachdr.). Harvard Business School Press.

Chornet, E., Valsecchi, B., Avila, Y., Nguyen, B., & Lavoie, J.-M. (2009). *Production of ethanol from methanol* (Patent No. US 2009/0221725 A1).

European Commission. (2018). *Industrial Symbiosis*. https://ec.europa.eu/environment/europeangreencapital/wp-content/uploads/2018/05/Industrial_Symbiosis.pdf

Gassmann, O., Daiber, M., & Enkel, E. (2011). The role of intermediaries in cross-industry innovation processes: The role of intermediaries. *R&D Management*, *41* (5), 457–469. https://doi.org/10.1111/j.1467-9310.2011.00651.x

Hahn, T. (2015). *Cross-Industry Innovation Process: Strategic Implications for Telecommunication Companies*. Springer Fachmedien Wiesbaden.

IN4climate.NRW. (n.d.). *How we work | IN4climate.NRW*. Retrieved 16 March 2020, from https://www.in4climate.nrw/en/about-us/how-we-work/.

IN4climate.NRW. (n.d.). *Industry | IN4climate.NRW*. Retrieved 16 March 2020, from https://www.in4climate.nrw/en/stakeholders/industry/.

IN4climate.NRW. (n.d.). *Newsletter: Aktuelles zur klimaneutralen Industrie | IN4climate.NRW*. Retrieved 16 March 2020, from https://www.in4climate.nrw/newsletter-anmelden/.

Inauen, M., & Schenker‐Wicki, A. (2011). The impact of outside‐in open innovation on innovation performance. *European Journal of Innovation Management*, *14* (4), 496–520. https://doi.org/10.1108/14601061111174934

Klewitz, J., & Hansen, E. G. (2014). Sustainability-oriented innovation of SMEs: A systematic review. *Journal of Cleaner Production*, *65*, 57–75. https://doi.org/10.1016/j.jclepro.2013.07.017

La Mantia, F. P., & Morreale, M. (2011). Green composites: A brief review. *Composites Part A: Applied Science and Manufacturing*, *42* (6), 579–588. https://doi.org/10.1016/j.compositesa.2011.01.017

Lema, R., Iizuka, M., & Walz, R. (2015). Introduction to low-carbon innovation and development: Insights and future challenges for research. *Innovation and Development*, *5* (2), 173–187. https://doi.org/10.1080/2157930X.2015.1065096

Liu, H., & Liang, X. (2011). Strategy for promoting low-carbon technology transfer to developing countries: The case of CCS. *Energy Policy*, *39* (6), 3106–3116. https://doi.org/10.1016/j.enpol.2011.02.051

Lodico, M. G., Spaulding, D. T., & Voegtle, K. H. (2010). *Methods in Educational Research: From Theory to Practice*. John Wiley & Sons.

Mölter, H., Kobiela, G., Vallentin, D., & Wehnert, Timon. (2017). *Formate zur Unterstützung von Tranformations- und Innovationsprozessen in Unternehmen. Virtuelles Institut 'Tranformation – Energiewende NRW'*. https://www.vi-transformation.de/wp-content/uploads/2017/04/Mölter_Formate-Innovationsprozesse.pdf

Nolf, B., Tsiakis, P., & Sambukumar, R. (2012). How to Implement an Effective Market Scan. *Supply & Demand Chain Executive*, *13* (1), 29–30.

Polzin, F. (2017). Mobilizing private finance for low-carbon innovation – A systematic review of barriers and solutions. *Renewable and Sustainable Energy Reviews*, *77*, 525–535. https://doi.org/10.1016/j.rser.2017.04.007

Rennings, K. (2000). Redefining innovation – Eco-innovation research and the contribution from ecological economics. *Ecological Economics*, *32* (2), 319–332. https://doi.org/10.1016/S0921-8009(99)00112-3

Roberts, E. B. (2007). Managing Invention and Innovation. *Research-Technology Management*, *50* (1), 35–54. https://doi.org/10.1080/08956308.2007.11657418

Schumpeter, J. A. (1942). *Capitalism, socialism and democracy* (1. Harper colophon ed., [Nachdr.]). HarperPerennial.

SCI4climate.NRW. (n.d.). *SCI4climate.NRW | IN4climate.NRW*. Retrieved 16 March 2020, from https://www.in4climate.nrw/ergebnisse/sci4climatenrw/.

SCI4climate.NRW. (n.d.). *SCI4climate.NRW – Lehrstuhl für Operations Management Prof. Dr. Grit Walther*. Retrieved 16 March 2020, from https://www.om.rwth-aachen.de/laufende-projekte/sci4-climate-nrw/.

SCI4climate.NRW. (n.d.). *Wissenschaft: Kompetenzzentrum SCI4climate.NRW | IN4climate.NRW*. Retrieved 16 March 2020, from https://www.in4climate.nrw/akteure/wissenschaft/.

Stolte, E. (2018, February 19). Five minutes from trash to ethanol: Edmonton's longdelayed Enerkem plant explained. *Edmonton Journal*.

Tönjes, A., Mölter, H., Pastowski, A., & Witte, K. (2019). *Summary of Decarbonisation Case Studies*. Retrieved 16 March 2020, from https://www.reinvent-project.eu/documentation.

Wesseling, J. H., Lechtenböhmer, S., Åhman, M., Nilsson, L. J., Worrell, E., & Coenen, L. (2017). The transition of energy intensive processing industries towards deep decarbonization: Characteristics and implications for future research. *Renewable and Sustainable Energy Reviews*, *79*, 1303–1313. https://doi.org/10.1016/j.rser.2017.05.156

World Economic Forum. (2012). *Chesbrough: Inside-out and Outside-in Innovation.* https://www.youtube.com/watch?v=02tCs3oKovc

Wüstenhagen, R. (2008). *Sustainable Innovation and Entrepreneurship*. https://doi.org/10.4337/9781848441552

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